A METHODOLOGY TO OPTIMIZE THE LIFETIME OF HYBRIDE COMPOSITE STRUCTURES: APPLICATION TO HIGH PRESSURE HYDROGEN TANKS

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SUMMARY

The present paper presents a method to design a 700 bar vessel which is a combination of a steel liner and a composite reinforcement. A well-proportioning method of the composite part is shown so as to overcome the fatigue problem of the tank under a cyclic high pressure.

Keywords: Hydrogen, high pressure vessel, fatigue, optimization, composite reinforcement, filament winding

I. INTRODUCTION

Research for alternative sources of energy to fossil fuels unquestionably is a challenge, economically and environmentally speaking. It is obvious that within this context, hydrogen is particularly interesting. It is the most promising source of energy regarding its calorific power and non polluting use. Nevertheless, in order to respond to economic and environmental criteria, hydrogen production and storage have to be improved. The present paper only aims at studying the gaseous hydrogen storage. One can notice that other type of storage exist using hydrogen in a liquid for or using metal hybrid such as $LaNi_5$.

Compressed gas storage can be realized by the use of four types of vessels:

- Type 1 refers to an all metal cylinder,
- Type 2 is a load-bearing metal liner hoop wrapped with resin-impregnated continuous fibre,
- Type 3 is a non-load-bearing metal liner - which prevents gas diffusion - wrapped with resin-impregnated continuous filament which is used as a mechanical strengthening piece (figure 1),
- Type 4 refers to a non-load-bearing non-metal liner - which prevents gas diffusion - wrapped with resin-impregnated continuous filament.

The fibre is generally a carbon fibre. This work focuses on gaseous storage under high pressure (700 bar) using a type III vessel.

The problem with this type of high pressure vessel is the early explosion when it is subjected to cyclic pressures. To solve this problem, the components – steel liner and composite – have to be well-proportioned.

Figure 1: Section of a type III vessel

A. Example: 1D case

For a good understanding of the problem, a short presentation on a 1D case is presented. Remarks concerning the latter can be used to solve a 3D case.

1. Composite

The composite behaviour is considered to be elasto-fragile. The failure stress of carbon fibre is approximately 3000 MPa with a 2% quasi-elastic strain. In reality, the composite reinforcement of a type III vessel is a bi-component with carbon fibres which are impregnated in an epoxy resin. This remark leads to 2000 MPa in strength (when the volume of fibre represents a ratio around to 2/3 of the total of the volume). The maximum strain of the composite part is the one of the fibre, that is to say a 2% maximum strain.
As far as fatigue is concerned, composite withstand very well, the damage level and the S-N curve (Wolher curve) slope are low. As a consequence, carbon/epoxy composite has a good resistance in fatigue in the direction of fibres.

2. Metal liner

In this study, the behaviour of the metal liner is viscoplastic (with a weak viscosity) and damageable. Contrary to the composite SN curve slope, the one of the metal is more important. For that reason, the critic strain for non-failure decreases with the number of cycles of loadings. One can notice that this phenomenon depends on the type of metal (chemical composition, manufacturing process, heat treatment) and on the temperature of use.

3. Assembly

One considers an assembly composed of a metal liner and a composite. The two components are supposed to be connected and that there is no space between their interfaces. If this assembly is submitted to a tensile effort, the latter is shared out among both the materials whereas the strain is the same.

For a static loading, composite resistance limits the static resistance of the assembly because of the steel plastification, the majority of the stress is exerted on the composite.
For a cyclic loading, the critical strain of the steel decreases faster than the one of the composite. So, metal strain has a significant effect on the fatigue failure of the assembly.

To conclude, for a long fatigue life, one has to reduce the strains during cyclic loading. It can be realized by:

- Transferring the load to the composite to reduce the global strain. That amounts to over-proportioning the static case and that implies a higher price of the assembly.
- Or using a metal which has a good behaviour and whose strains do not decrease when it is submitted to cyclic loads.

B. Generalization: 3D case

The loading in a type III vessel is less explicit than the uniaxial case presented before. Indeed the state of stress is complex insofar as during the pressure loading, changes of stress directions appear. This phenomenon is caused by the plasticity of the metal liner which implies a redistribution of the stresses on the composite reinforcement which is anisotropic. The prediction of the transfer is difficult, particularly in a fatigue analysis. To overcome the risk of a bad stress transfer and a short lifetime of the structure, the study aims at finding a strain criterion on the metal which allows an infinite lifetime or at least 15000 cycles.

II. ANALYSIS METHOD

The aim of this study is to analyze the behaviour of a tank under fatigue and to optimize the reinforcement by composite. The basis of the optimization is to reduce the strain of the liner in a domain that does not allow a breaking under cyclic loads. This is why, composite has to be well-proportioned to preserve the lifetime of the tank.

To solve this problem, experiments have to be carried out on the steel to have a good approximation of its behaviour. For a correct modelling of the viscoplastic metal behaviour, some tests on samples of the liner have to be performed. A summary of those experiments is given in next paragraph. Once the behaviour identified, a finite element analysis is launched to establish a strain criterion on the steel liner under cyclic loads.

The second step consists in an analytic calculation of the best angles sequence of composite which allows the liner to keep in the strain domain defined before. This computation has been developed according to Chapelle and Perreux method [2]. A pipe made of a metal liner reinforced by composite is studied. The composite is made of polymer reinforced by carbon fibre. The damage of the composite is neglected - because the strain range is very low – and the interface between the liner and the reinforcement is supposed to be perfect. The composite data are given by the manufacturer and those of the metal liner are determined by the tests.

Finally, we will manufacture a type III vessel according to the first and second step study and will exert a cyclic pressure on this HP tank. The aim of this study is to resist 1050 bar for 15000 cycles. Comparing resistance tests in fatigue with simulations, the vessel would be optimized successfully. One can notice that nowadays, tests on vessels with a 1050 bar cyclic pressure conducts to a lifetime that is rarely superior to 1000 cycles.

Figure 2 summarizes analysis and optimization method described above.

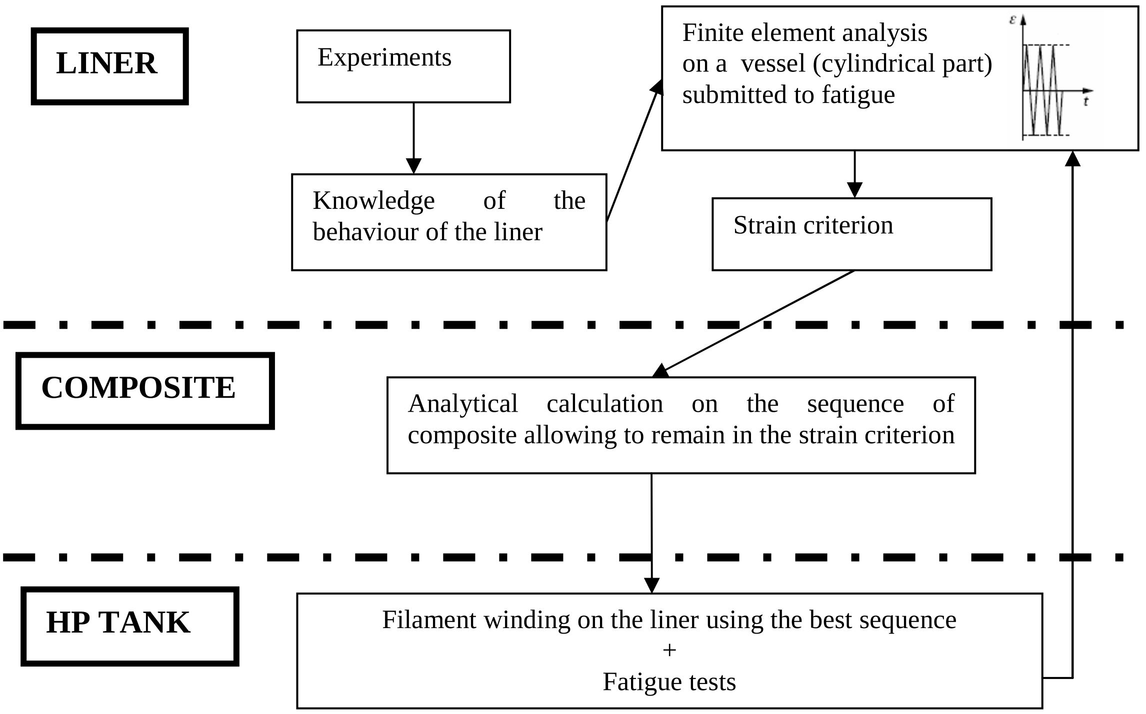

Figure 2: Method of analysis and optimization of the fatigue life of HP tanks

III. KNOWLEDGE AND MODELLING OF THE BEHAVIOUR OF THE LINER

The behaviour of the steel used in the HP tank is largely known but due to the manufacturing process and the heat treatment, it is necessary to test the metal of the liner precisely. The data of the literature gives precious information on the plan of experiments. Indeed, as a softening effect and a ratcheting effect appear during cyclic loading on this metal, a plan of experiments is performed:

- Static tests on samples to access to constants such as Young modulus and Poisson ratio, yield strength, tensile strength and breaking stress,
- Cyclic tractions/compressions on samples with a ratio $\frac{\varepsilon_{\min}}{\varepsilon_{\max}} = -1$ by varying the value of $\varepsilon_{\max}$ to understand the steel fatigue behaviour [3-4] and to quantify the softening. It also permits to model the behaviour of the steel by identifying parameter of the model
- Cyclic tractions/compressions on samples with a ratio $\sigma_{mean} \neq 0$ by varying the value of $\sigma_{\max}$ to evaluate the ratcheting effect and to show the influence of the mean stress on the lifetime of the structure.
- Creep test to determine the viscous parameters.

Specimens are manufactured from the steel liner by wire Electrical Discharge Machining (wire EDM). The machine - a CHARMILLES ROBOFIL 2510 TW - allows a good precision in dimensions, a high speed of manufacturing (up to 500 mm^2 per minute), and an easy implementation (programming, monitoring of manufacturing). The geometry of the specimens is represented figure 3:

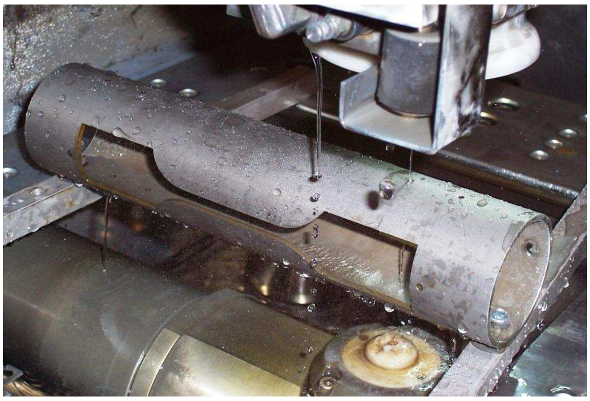

Figure 3: Manufacturing of the specimens by wire EDM

Experiments are done on an INSTRON 8501 device. To measure the strains, two extensometers are glued on the middle part of the samples.

As far as the static tests are concerned, it appears that this material presents a ductile behaviour. The parameters obtained by these experiments are the Young Modulus (E=200000 MPa), the tensile strength ($\sigma_R = 1000$ MPa), the 0.2% yield strength ($\sigma_Y = 800$ MPa) and a 6% uniform elongation and a 0.32 Poisson ratio.

Cyclic tests are done to model the behaviour of the metal. We choose to use 3 hardening variables (two kinematic and one isotropic variables), to have a good quality of modelling the ratcheting effect, the softening effect and the hysteresis loop (figure 4) [1].

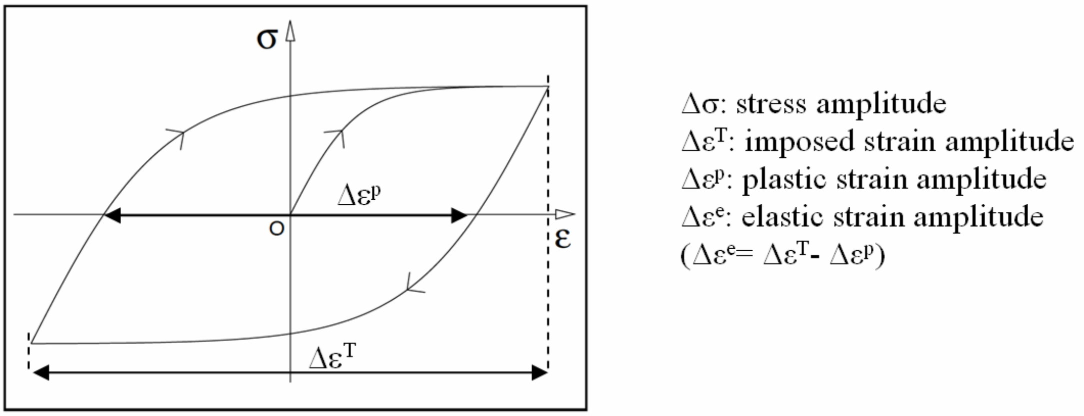

Figure 4: A hysteresis loop [1]

One can notice that an identification of 8 parameters (2 parameters per hardening variable and two viscous parameters) is necessary. The author used the classical Levenberg Marquardt method for this identification. A numerical tool developed at the Laboratory was used. An example of comparison between test and simulation is provided on figure 5.

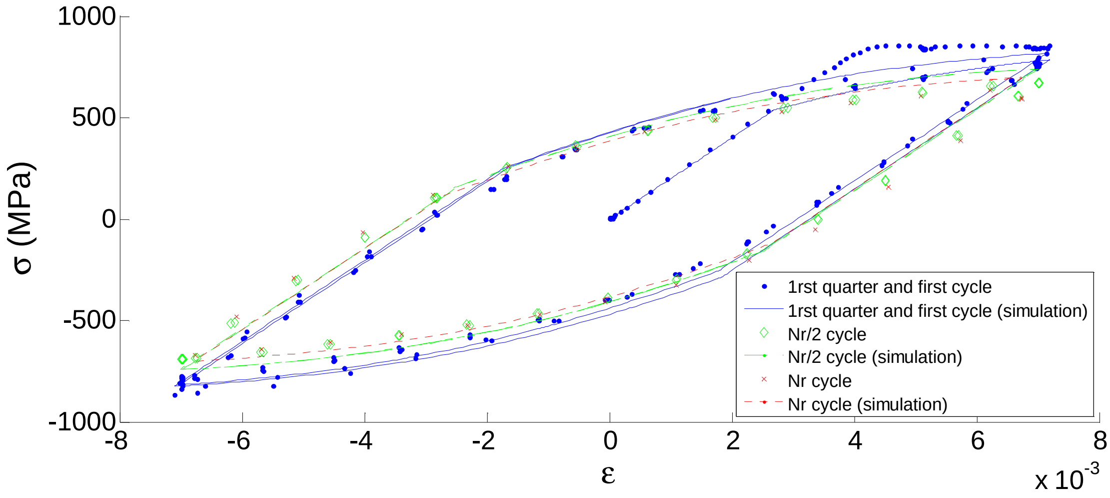

Figure 5: Modelling of the behaviour

The next step of the method is a finite element analysis that will allow to find the strain criterion. The software used for this analysis is Comsol Multiphysics© that allows to enter easily our proper hardening law by introducing partial differential equations in the program. This software is also interesting because it is possible to introduce thermal effect which appears during the loading in pressure. In the present study, this aspect is not considered.

The following analysis focuses on the cylindrical section of the hydrogen tank subjected to internal pressure with closed-end effect loading insofar as the failure of the vessel mostly happens in this zone. This choice is justified by the fact that the majority of the vessel failure appears in this zone. Thanks to a damage criterion constructed from the tests on steel samples, it is know possible to construct a strain criterion by loading the cylindrical part made of steel

Moreover, this comsol simulation is also interesting because one can understand easily the transfer of the load which happens in a high pressure tank during its lifetime by introducing a composite part around the liner.

IV. DETERMINING OF THE BEST SEQUENCE OF REINFORCEMENT

Once the strain criterion of the liner is established, the sequence of the composite reinforcement able to resist and to confine the strains of the liner in this domain has to be found. A matlab program was devised thanks to –in particular - Chapelle and Perreux work. The damage of the composite is not introduced in the analytic model as it was specified before. Figure 6 presents the process of this calculation. Entry variables are those resumed in tables 1 and 2 and the winding sequence around the liner. Output data are displacement/strain/stress for each layer of the composite and of the liner. One can notice that this programme can take into account the liner and the evolution of its plasticity by considering the liner as a multi-layer. This metal modelling allows to represent the gradual plasticity in the thickness.

The method of calculation of the radial displacement/strains/stresses is not explained in this paper. For further explanations, see [2][5-8]. Furthermore, Chapelle and Perreux – who works on an aluminium alloy – use the law of Hollomon for fitting the tensile curve [2]. This law is not valuable in the case of steel with a high yield stress σ_Y in comparison with the plastic domain. To have a better modelling, a Ludwick law is introduced: $\sigma = \sigma_Y + K\varepsilon^{\alpha}$. K and α allow to define the plastic behaviour of the liner and are determined from the tensile test curve.

To predict possible failure of the vessel, two criteria were introduced: if the equivalent Von Mises stress σ_{Eq} is higher than the yield strength of the steel or the Tsaï Wu criterion is not respected for the composite, the calculation ends [9].

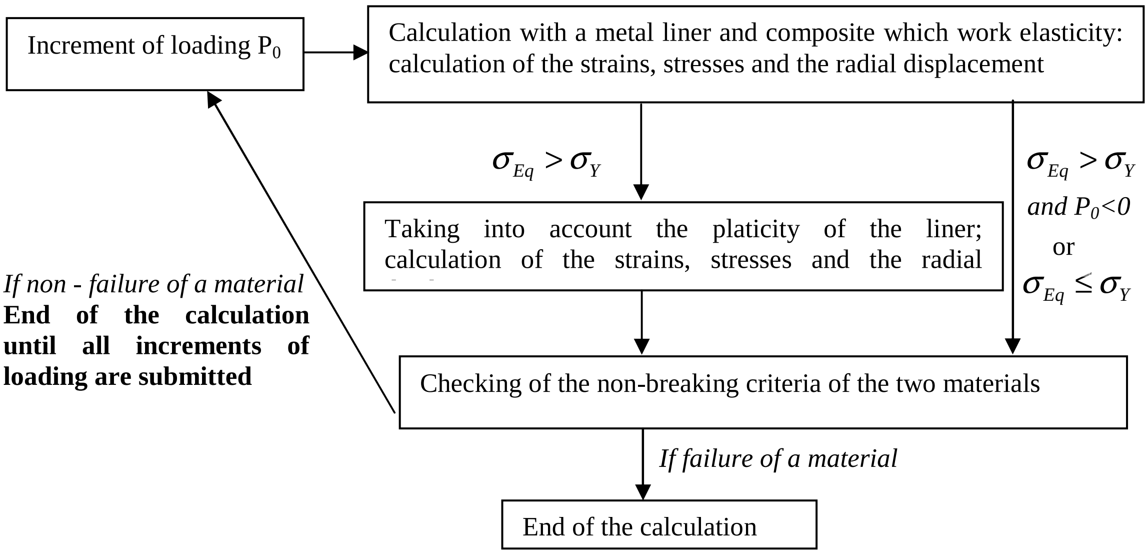

Figure 6: Methodology of calculation

Steel	
Young's modulus E	200 GPa
Poisson ratio ν	0.32
Yield strength σ_Y	800 MPa
Tensile strength σ_R	1000 MPa
Thickness	3 mm

Table 1: Properties of the steel [1]

Composite		
Young's modulus of a layer in the fibre direction	E_L	150 GPa
Young's modulus of a layer in the transverse direction	E_T	11 GPa
Shear modulus	G	4 GPa
Poisson ratio	ν_{LT}	0.3
Poisson ratio	ν_{TT}	0.49
Tensile strength in the fibre direction	X_T	1500 MPa
Compression strength in the fibre direction	X_c	1500 MPa
Tensile strength in the transverse direction	Y_T	50 MPa
Compression strength in the transverse direction	Y_c	250 MPa
Shear strength	S_{LT}	70 MPa
Thickness of a layer	e_c	0.27 mm

Table 2: Properties of the composite [1]

The results of a simulation with a $[(+15°,-15°)_5, (90)_{20}]$ stacking sequence are given in figure 7. The pressure inside the pipe rises from 0 to 1050 bar during the first 500 seconds and then decreases to 0 bar during the next 500 seconds. The inner radius of the liner is 44 mm. One can notice that after being submitted to this loading/unloading in pressure, the liner is in compression due to its plasticity and to the elastic return of the composite in its initial position. Figure 7, by showing the evolution of all strains of the metal, guides the designer in the choice of the geometry of the reinforcement.

Knowing the strain criterion of the metal liner, it is now easy to find a winding sequence of composite. The best sequence can be found using a method such as a genetic algorithm by minimizing the weight of composite. The consequences of the optimization are a lower weight of the vessel – which is aimed at being board in a vehicle -, a lower time of manufacturing process of the vessel and a lower price in raw materials.

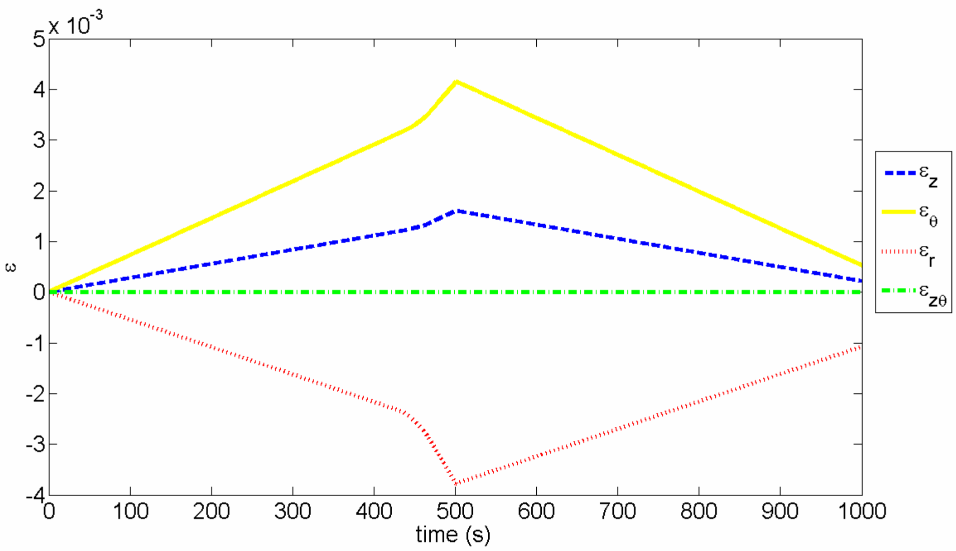

Figure 7: Example of simulation calculated for the medium radius of the liner

V. FATIGUE ON A PRESSURE VESSEL

A filament winding is now done on a 2.2 L steel liner. The manufacturing is realized by the MaHyTec company. The stacking sequence is the one of the previous simulation. The composite reinforcement of composed of thirty layers. This liner is tested under a cyclic oil pressure. The speed of the test is 233 bar.s^{-1}. The fluid is oil. The minimum and maximum pressures are respectively 0 and 1050 bar (figure 8). While in a majority of cases a cracking appears in the first hundreds cycles, the tested HP tanks resists more than 5000 cycles. This experiment proves that the fatigue of type III could be improved with success by using the proposed method.

Figure 8 : A 1050 bar fatigue test on a type III vessel

VI. PERSPECTIVES AND CONCLUSION

This study underlines the fact that for a higher lifetime of the vessel, the main point to improve is the proportioning of the composite reinforcement. The first experiments on the steel allowed to complete the database required to the liner modelling. Thus, thanks to the studies of the strain-stress hysteresis loops with a variable ratio $\varepsilon_{min}/\ \varepsilon_{max}$ and of the sensibility to ratcheting effect and a finite elements analysis, the determining of a strain criterion is possible.

A tool has been developed to calculate the strains and stress inside a pipe composed of a steel-composite multi-layer. The later allows, from a defined strain criterion of the steel, to find a sequence of composite allowing to keep the liner in this strain domain. A work of optimization on the winding sequence of the reinforcement is viewed in order that hydrogen gas storage will be competitive.

The result of tests on HP vessels under cycling internal pressure is very hopeful to a rapid resolution of those problems of fatigue.

VII. ACKNOWLEDGMENT

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